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13. ABSTRACT *(Maximum 200 words)*

The research reported herein, has led to significant advances in high resolution spectral analysis of time-series---impacting upon sensor technology and upon application areas such as radar and medical imaging. The research is based on the initial discovery that (weighted) covariance statistics. i.e., statistics which are more general than the traditional autocorrelation function, allow for a superior resolution of the power spectrum of a time-series. The work comprises of the development of a computational theory and the development of a spectrum of analytical tools for (i) parametrizing all power spectra which are consistent with given data5 (ii) incorporating prior information in spectral estimation, and (iii) fusion of covariance statistics obtained by different sensors. Research on a parallel effort in control design methodologies has led to advances in robustness analysis and optimal control of oscillatory systems.

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Tryphon T. Georgiou
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FINAL REPORT

Advances in Control and Signal processing

Submitted to the
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Table of Contents

Summary

The research reported herein, which has been supported by the Air Force Office for Scientific Research under Grant No. AF/F49620-00-1-0078, has led to the development of theory and tools for high resolution spectral analysis of signals—impacting upon sensor technology and upon application areas such as radar and medical imaging. Parallel reseach, conducted under the same AFOSR support, has also led to new results in Robust and Optimal control for certain types of nonlinear and oscillatory systems.

The main thrust of the research has been on the subject of high resolution spectral analysis. The advances we report on are a culmination of efforts by the PI and his co-workers over a number of years. The key elements are:

1. The discovery that (weighted) covariance statistics, i.e., statistics which are more general than the traditional autocorrelation function, allow for a superior resolution of the power spectrum of a time-series.
2. The development of a computational theory for parametrizing all power spectra of bounded complexity, which are consistent with given statistics of a time series.
3. The development of an approximation theory for *incorporating prior information* on the power spectrum, and for *fusion* of data in the form second order statistics which have been obtained by different sensors.

A U.S. Patent (No. 6,400,310 issued June 4, 2002) has been issued to the PI and his co-workers (Chris Byrnes and Anders Lindquist) on related technology for application to speech analysis and to the analysis of radar signals. The theory and methodologies developed under the grant are expected to have a major impact in applications such as estimation of direction-of-arrival in radar and sonar, synthetic aperture radar, beamforming and antena focusing, as well as speech recognition and speech synthesis.

The research supported by the present grant resulted in 10 journal papers, 6 book chapters, 9 conference papers, one Ph.D. thesis and one M.S. thesis. These are are listed below.

1 Research Publications

The research supported by the present grant resulted in 10 journal papers, 6 book chapters, 9 conference papers, one Ph.D. thesis and one M.S. thesis. These are are listed below. They can be classified broadly into categories as follows:

High resolution spectral analysis: 2,6,7,8,10,11,14,15,16,17,18,22,24,25,27.

Convex optimization and distance measures for power spectra: 10,14,15.

Mixing/fusion of statistics: 15,16.

Imaging techniques: 13, 22.

Analytic interpolation theory/applications: 1,6.

Robust control: 3,4,6,19,20,21,23,26.

Sampled-data control: 12.

Journal publications

1. T.T. Georgiou, "Analytic Interpolation and the Degree Constraint," *Int. J. Applied Mathematics and Computer Science*, Special issue, guest editors M. Fliess and A. El Jai, January 2001, vol. 11, No 1, 101-109.

2. T.T. Georgiou, "Spectral Estimation by Selective Harmonic Amplification," *IEEE Trans. on Automatic Control*, **46(1)**: 29-42, January 2001.

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5. U. Walther, T.T. Georgiou and A. Tannenbaum, "On the Computation of Switching Surfaces in Optimal Control: A Groebner Basis Approach," *IEEE Trans. on Automatic Control*, April 2001.

6. C. Byrnes, T.T. Georgiou, and A. Lindquist, "A Generalized Entropy Criterion for Nevanlinna-Pick Interpolation: A Convex Optimization Approach to certain problems in Systems and Control", *IEEE Trans. on Automatic Control*, **45(6):** 822-839, June 2001.

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9. S. Varigonda, T.T. Georgiou, and P. Daoutidis, "Numerical Solution of the Optimal Periodic Control Problem using Differential Flatness," *IEEE Trans. on Automatic Control*, to appear, 2003.

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Book Chapters

11. C. I. Byrnes, T. T. Georgiou and A. Lindquist, "Advances in high-resolution spectral estimation," System Theory: Modeling, Analysis and Control,T.E. Djaferis and I.C. Schick (editors), Kluwer Academic Publishers, 2000, 167–179.

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16. T.T. Georgiou, "The mixing of state covariances," Multidisciplinary Research in Control: The Mohammed Dahleh Symposium 2002. Eds. L. Giarre' and B. Bamieh, Lecture Notes in Control and Information Sciences N. 289, Springer-Verlag, Berlin, 2003.

Refereed Conference Publications

17. T.T. Georgiou, "Subspace analysis of covariances," Proceedings of the IEEE Conf. on Accoustics, Speech, and Signal Processing, Istanbul, June 2000.

18. T.T. Georgiou, "Co-invariant subspaces in array processing," Proceedings of the 2000 international workshop on the Mathematical Theory of Networks and Systems, Perpignon, France, June 2000.

19. S. Varigonda, T. T. Georgiou, R. A. Siegel and P. Daoutidis, "Computation of optimal periodic control for chemical processes," 2000 AIChE Annual Meeting, November 2000, Los Angeles, CA (abstract).

20. T.T. Georgiou and M.C. Smith, "Robustness of a relaxation oscillator," Proceedings of the 2000 Conf. on Decision and Control, Sydney, Australia, December 2000.

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Theses

26. Subbarao Varigonda, *Robust control of periodic systems with application to the control of chemical reactors*, Ph.D. Thesis, Dept. of Chemical Eng. and Material Sciences, University of Minnesota, March 2001.

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2 Accomplished Research

"Modern nonlinear methods" for spectral analysis began their appearance in the early 1980's and, invariably, relied on *autocorrelation/covariance statistics* of a given time-series (originating from speech, radar, sonar, etc.), The goal of these methods was to overcome limitations on resolution in linear (FFT-based) methods which stem from the time-frequency uncertainty principle. The theory and methods which were introduced in the research reported herein may be seen as "post-modern" in that they are based on an evolution of the ideas underlying the aforementioned "modern nonlinear methods" of the 1980's and 1990's; these being exemplified by the maximum entropy (MEM), the maximum likelihood (Capon) and various subspace identification methods (e.g., MUSIC, ESPRIT).

In order to explain the new ideas we briefly describe the basic setting of the "modern nonlinear methods": Denote by $R_k := E\{u(\ell)u(\ell+k)\}$ $(k = 0, 1, \ldots)$ the autocorrelation sequence of a (zero-mean) stochastic process $u(k)$. Typically, this is estimated from the observation record. The power spectrum in the simplest case of a scalar real $u(k)$, is:

$$\Phi_{uu}(\theta) \sim \ldots + R_2 e^{-2j\theta} + R_1 e^{-j\theta} + R_0 + R_1 e^{j\theta} + R_2 e^{2j\theta} \ldots.$$

The one-sided "half" of the series

$$f_{uu}(z) = \frac{1}{2}R_0 + R_1 z + R_2 z^2 + \ldots$$

is a central object in our theory. It is now easily seen how the standard autocorrelation sequence specifies f_{uu} and its derivatives at the origin, i.e., $f_{uu}(0) = \frac{1}{2}R_0$, $\frac{d}{dz}f_{uu}(0) = R_1$, etc. At the same time, f_{uu} has *positive-real* part (since $\Phi_{uu}(\theta) \geq 0$). In fact "positive realness" is what characterizes such "half spectra" and the autocorrelation statistics lead us naturally to finding suitable "positive real interpolants" for the estimated statistics. Any such interpolant is a power spectrum which is consistent with our data.

The "modern nonlinear methods", in one way or another, lead to specific interpolants for a partial autocorrelation sequence $R_0, R_1, \ldots, R_n$. It should be noted that, in general, there is a family of interpolants which are all consistent with such partial statistics. Hence, there is a plethora of "methods." All such methods are often justified as seeking power spectra with specific properties (e.g., maximum entropy, etc.).

The viewpoint which has led to advances reported herein can be explained by emphasizing the following facts:

(a) Covariance statistics represent constraints that define the family of power spectra which are consistent with our data.

(b) The size of this family represents uncertainty about the "true" power spectrum.

(c) An "algorithm" or a "method" represents a specific selection of a power spectrum which is consistent and (possibly) incorporates prior information.

Each of these facts deserves special attention. In fact, this research has extended, explored, and integrated the above so as to form the basis of a theory for high resolution spectral analysis.

2.1 High resolution spectral analysis

With regard to item (a), we have made a crucial *observation* [2] which forms the basis of new very high resolution methods:
If the time-series $u(k)$ is processed by a first-order filter as shown in Figure 1,then the covariance of the state/output $x(k)$ relates to the value of the corresponding "half-spectrum" f_{uu} via

$$f_{uu}(p) = \frac{1-p^2}{2} E\{x(k)^2\}.$$

Such a filter could represent virtual (algorithmic processing of $u(k)$) or actual dynamics of sensory aparatus.

The significant new element in the above is that specific information on f_{uu} can now be retrieved via such "*generalized statistics*." Such information pertains typically to power distribution in a specific harmonic interval. Thus, we have the following general approach:

1. construct a filter bank as in Figure 2, with poles selected so as to "magnify" the effect of spectral power of the input in a targeted harmonic interval,
2. obtain state statistics and interpret these as interpolation data for the "half-spectrum" f_{uu} in the vicinity of the frequency band of interest, and then
3. derive suitable spectral estimates Φ_{uu}, e.g., by using general analytic interpolation theory identifying an "interpolant" f_{uu} and setting $\Phi_{uu} = 2\mathrm{Re} f_{uu}$.

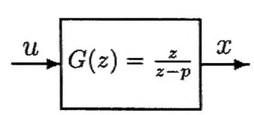


Figure 1: First-order filter.

A more general senario, which incorporates ordinary autocorrelation/covariance data as a special case, is possible. To this end we may consider a general linear structure for the processing aparatus (filter bank). In this case we take $x = (x_1, \ldots, x_n)$ the state of the state of a linear filter

$$x(k) = Ax(k-1) + Bu(k).$$

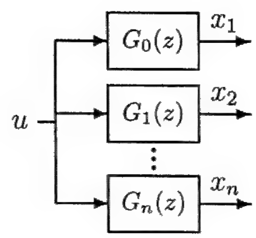


Figure 2: Bank of filters.

The filter parameters A, B could model a combination of actual dynamics (dynamics of a sensory aparatus or of the mechanism generating observed quantities) as well as virtual dynamics (representing algorithmic post processing of $u(k)$). The state covariance

$$\Sigma := E\{x(k)x(k)'\}$$

has *a special structure inherited by a combination of the filter dynamics and of the spectral content of* $u(k)$. For instance, the case of an ordinary partial autocorrelation sequence corresponds to choosing the parameters A, B as the state matrices of a tapped delay line where $x_n(k) = u(k)$ and for $\ell = 1, \ldots, n-1$, $x_\ell(k) = x_{\ell+1}$. In that case, Σ is simply an ordinary Toeplitz matrix $[R_{k-m}]_{k,m=1}^{n}$.

The relevant mathematical theory has been fully developed in [11–14]. Briefly, the covariance matrix Σ is characterized by the condition

$$\text{rank}\begin{bmatrix} \Sigma - A\Sigma A^* & B \\ B^* & 0 \end{bmatrix} = 2\text{rank}(B).$$

The above formula applies to the general case where $u(k)$ is vectorial (and A, B are sized accordingly). This condition is necessary and sufficient for the solvability of

$$\Sigma - A\Sigma A^* = BH + H^*B^*$$

for some matrix H of compatible dimensions. In fact, H encapsulates the spectral power within the bandwidth of the *input-to-state* filter with parameters (A, B). In [11–14], explicit formulae have been given for:

1. Parametrizing the whole family of power spectra that are consistent with the "generalized statistics" Σ (e.g., see [14, page 1818, Theorem 2] and also [13, Theorem 2]). The parametrization, besides being of theoretical interest, can be used to obtain algorithms/methods for constructing power spectra consistent with specific prior information.

2. Algorithms and methods analogous to the classical Maximum Entropy, Capon, and Subspace identification techniques, but based on generalized statistics instead, have been developed and tested on a variety of case studies in [11, 14], and [12, Sections IV, V, VI, and VII].

The selection of filter parameters A, B, when such parameters represent virtual/algorithmic dynamics, is discussed in [12, Section VIII] and also in [22]. In particular, [22] discusses tradoffs between resolution of a spectral estimator (interpolant) and its own variance. This is an important issue which stems from the fact that generalized covariance statistics are computed based on a finite observation record and the variance of the "generalized covariance" estimates is passed on to the interpolant and hence, to the corresponding power spectrum as well.

2.2 Convex optimization & distance measures

Analytic interpolation has its origins in the so-called moment problem where a distribution μ is sought to match given moments

$$R_k = \int g_k(\theta) d\mu(\theta),$$

with g_k given basis functions. It is easy to recognize $g_k(\theta) = e^{jk\theta}$ and $d\mu(\theta) = \Phi_{uu}(\theta)$ for the case where R_k are autocorrelation/covariance samples and $d\mu$ a spectral distribution of the stochastic process $u(k)$. The more general case of generalized statistics Σ introduced aboove, leads to an analogous expression:

$$H = \int_{-\pi}^{\pi} G(e^{j\theta}) d\mu(\theta)$$

where $G(z) = (I - zA)^{-1}B$, and H obtained from Σ via solving $\Sigma - A\Sigma A^* = BH + H^*B^*$; see [13]. In this latter formulation the entries of H represent moments of the spectral distribution with respect to generalized kernel functions which are precisely the entries of $G(z)$.

A long standing problem (introduced in [6–8] and motivated by work of D.C. Youla in circuit theory and R.E. Kalman in stochastic realization) called for the explicit parametrization of distributions $d\mu$ of bounded complexity. The notion of complexity can be conveniently expressed in the form of a degree constraint on the spectral density function Φ_{uu} [8]. This problem has been solved in [1, 2, 9, 10] for the general case where interpolation data are given in the form of a state covariance Σ. On-going work [3] explores mathematical extensions to generalized analytic interpolation with complexity constraint for the case where the input-to-state filter $G(z) = (I - zA)^{-1}B$ is ∞-dimensional (i.e., when A, B are no longer finite matrices).

The relevance of the work in spectral analysis stems from the fact that the degree constraint restricts in a natural way the set of admissible spectra, and thereby, restricts the uncertainty about the "true" power spectrum (see [1, 2]).

In an effort to devise algorithmic tools for computing bounded complexity solutions, a certain *convex functional* was introduced which initially was considered only as a technical tool ([1, 4]). It gradually became clear that this functional can be reinterpreted as a relative entropy between power spectra. This was pursued in [18] whereas analogous functionals have been explored in [16, 17] for addressing numerical issues of estimating admissible state covariances from an observation record. We

briefly describe the main findings which are fully documented in the aforementioned publications. Given two power spectral density functions Ψ, Φ define as a distance measure between the two via the expression

$$\mathbb{I}(\Psi, \Phi) := \int \Psi \left(\log(\Phi) - \log(\Psi)\right) d\theta.$$

This quantity is reminiscent of the Kullback-Leibler distance between probability distribution functions, and in fact, for spectral density functions it of course has similar convexity properties. Thus, it can serve a *bona fide* distance measure (see [18]) and moreover, the (∞-dimensional) optimization problem

$$\min\{\mathbb{I}(\Psi, \Phi) \text{ over } \Phi \ : \ \int G(e^{j\theta})\Phi(\theta)d\theta = H\}$$

has a unique solution which can be expressed in closed form in terms of the data A, B, H (H obtained from a state covariance Σ as before) and a matrix Λ (of Lagrange multipliers and of the same size as Σ) which can be obtained by solving a *finite-dimensional convex optimization problem.*

During case studies, we often encountered a situation where the estimated statistics Σ failed to satisfy $\Sigma - A\Sigma A^* = BH + H^*B^*$ (as predicted by the theory) due to estimation errors. The consequence of errors introduced in the process become significant. In such cases, we have found that the following functional which was introduced by von Neumann for measuring distance between density matrices of quantum systems [23]

$$\mathbb{I}(\hat{\Sigma}, \Sigma) := \text{trace}\{\hat{\Sigma}(\log \Sigma - \log \hat{\Sigma})\}$$

can similarly serve as a distance measure between covariance matrices, and the relevant optimization problem

$$\min \left\{\mathbb{I}(\hat{\Sigma}, \Sigma) : \Sigma \text{ such that } \Sigma - A\Sigma A^* = BH + H^*B^* \text{ for some } H\right\},$$

where $\hat{\Sigma}$ is the sample state-covariance, is well-behaved. This is documented in [16, 17].

2.3 Mixing/fusion of statistics

Data acquisition and integration, in general, present a number of challenging issues. In the context of spectral analysis based on second order statistics, it is often important to integrate data originating from different sensors (e.g., different antena arrays). Results relevant to certain special but common situation have been documented in [15].

2.4 Imaging techniques

In [24] a new methodology has been presented for high resolution image processing and knowledge-based segmentation for SAR imagery. We expect that the viewpoint advanced wil have a major impact on problems in radar and remote sensing.

2.5 Analytic interpolation theory

As explained and discussed in Subsection 2.2, results in [1, 2, 9] have solved a long standing problem in mathematics (introduced in [6–8] and motivated by work of D.C. Youla in circuit theory and R.E. Kalman in stochastic realization).

2.6 Robust and Sampled-data control

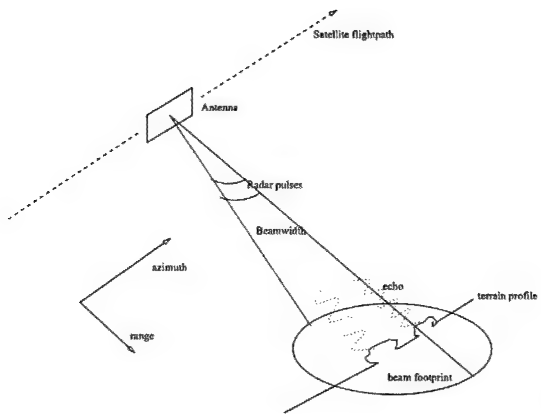
The problem of how to organize computations in a digital controller implementation is often overlooked. In [25] we document results and quantitive measures of robustness which may serve as a guideline for selecting one particular controller implementation over another. References [27, 30–33, 35] document results on robustness of oscillatory systems as well as a new methodology for design of optimal periodic control.

References [29] and [26] present two different applications of the modern algebra-geometric tools of Groebner bases to time-optimal control and back-projection image reconstruction, respectively. Interest in Groebner bases stems from the ease with which, closed form solutions can be obtained in certain classes of suitably formulated problems. Work along these topics is on-going.

2.7 Application studies

Application studies are reported in [5, 19, 21, 24]. The work reported therein focuses on the use of the high resolution methods that have been developed in this research, in the context of speech analysis [5, 19], in non-invasive temperature sensing for medical applications (e.g., non-invasive heat treatment of cancer) [21], and in Synthetic Aperture imaging [24]. Below, a brief outline of how the methods apply to SAR imaging is given. Details have been documented in the aforementioned publications.

SAR imaging is a mature subject with a history and technological developments of over 40 years. A classical text on the subject is [37] to which the interested reader is refered to for a detail discussion of enabling technology and a wide range of applications. Extensive amount of SAR data, documentation and technology are available, e.g., [36]. SAR data are typically collected by a flying system (satelite, plane) as depicted in Figure 1, see [36, 37, 40]. The target area is illuminated by a series of electromagnetic pulses. The recorded echoes are analyzed into components according to the distance of the responsible scatterers (e.g., using matched filtering). The echoes from a particular distance range contain information about the profile and reflectivity of the relevant scatterers at that range. The information is encoded in the amplitude and the doppler shift of the reflected signal. E.g., positive doppler shift indicates a scatterer which is positioned more aft, etc. Spectral analysis of the echoed signal into Fourier components produces the amplitude and position of scatterers at each distance range—thereby generating a SAR image of the targeted area.

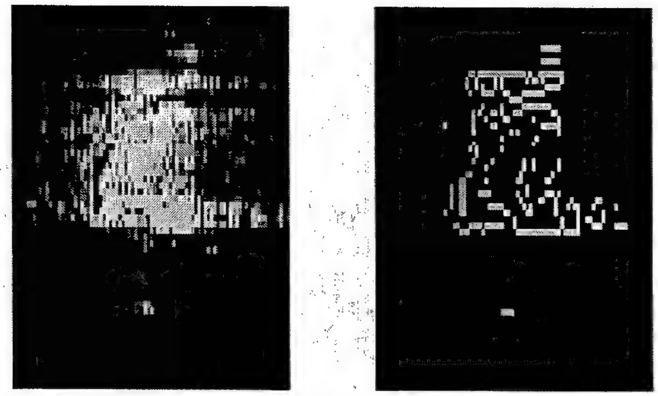


Synthetic Aperture Radar

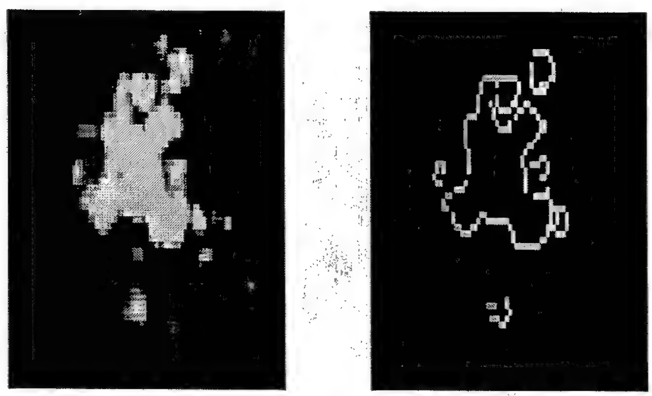
Analogous issues arise in sonar or radar applications which involve array of sensors [38]. A target area is illuminated and the direction of the reflected wave, as it impinges upon an antenna array, reveals the location of the scatterers. The spacial harmonics of the received signal across the elements of the antenna carry the useful information which may allow resolving the location of nearby scatterers.

Application of the new techniques for very high resolution spectral analysis and their relevance and performance when applied to SAR data are discussed in [24] along with a explanation on a novel approach for subsequent processing of SAR images using knowledge based segmentation and anisotropic smoothing. The high resolution methods are reminiscent of the so-called beamspace techniques [39] and are based on post processing of SAR data through a bank of input-to-state filters (as explained above and as detailed in e.g., [12, 14]). Each input-to-state filter is designed so as to achieve superior resolution in a partial spacial sector of the image. In the case of the images shown below the analog of the method of ESPRIT (as explained in detail in [12]) has been applied. This method produces a collection of spectral lines within the relevant spacial sectors; these lines correspond to individual scatterers of the SAR illuminating signal. The image is then pasted together by superimposing those individual scatterers identified in each sector.

Two images (of a T-72 tank using MSTAR data) are shown for comparison. The first image is generated using standard FFT-based technique, while the second, using high resolution ESPRIT-like method (as just noted). Next to each of the two images, the outline of the "target" is shown which has been highlighted using a standard (Matlab signal processing toolbox) edge detection technique. This last step underscores the difference in dynamical range between the two, which facilitates greatly target recognition and identification.



FFT-based image reconstruction and edge detection



high resolution imaging and edge detection

A detailed exposition of theory and computational issues underlying the new techniques has been documented in the cited publications.

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4 Ph.D. theses

1) Subbarao Varigonda, *Robust control of periodic systems with application to the control of chemical reactors*, Ph.D. Thesis, Dept. of Chemical Eng. and Material Sciences, University of Minnesota, March 2001.

2) A. Nasiri-Amini, *State Covariance Subspace Methods for Spectral Estimation,* MS Thesis, Dept. of Electrical and Computer Eng. University of Minnesota, June 2003.

5 Awards, Recognition

1. *Fellow of the IEEE*, January 2000.
2. *Board of Governors, IEEE Control Systems Society:* elected (January 2002).
3. *Hermes-Luh Professorship in Electrical Engineering,* University of Minnesota, 2002—
4. *1999 IEEE Control Systems Society G.S. Axelby Outstanding Paper Award,* for the paper: T.T. Georgiou and M.C. Smith "Robustness Analysis of Nonlinear Feedback Systems: An Input-Output Approach," *IEEE Trans. on Automatic Contr.*, 42(9): 1200-21, 1997.